

Validation of MODIS aerosol optical depth retrievals over a tropical urban site, Pune, India

Sanjay More¹, P. Pradeep Kumar¹, Pawan Gupta^{2,3}, P. C. S. Devara⁴, G. R. Ahers^{5*}

¹ Department of Atmospheric and Space Sciences, University of Pune – 07

² NASA Goddard Space Flight Center Greenbelt, MD 20771, USA

³ Universities Space Research Association, Greenbelt, MD 20771, USA

⁴ Indian Institute of Tropical Meteorology, Pune-08

⁵ Physics Department Nowrosjee Wadia College, Pune-01

**ahers.g.r@gmail.com*

Summary

This paper attempts to validate the MODIS dark target aerosol optical depth product over tropical urban location in India. The ground truth data used in this study has been collected using Microtops hand held sun-photometer on cloud free days during 2008-2010. AERONET measurements have also been compared against MODIS and Microtops. Aerosol properties derived from the AERONET over the same location have been analyzed as well. This is the first ever systematic validation of the MODIS aerosol products over Pune. MODIS AOD retrievals are well correlated with the AERONET and Microtops AODs. MODIS AODs underestimate during winter and overestimate during pre-monsoon. MODIS retrievals are capable of characterizing AOD distributions over Pune. Systematic error in the MODIS aerosol products needs further investigation. Single scattering albedo shows seasonal variability, winter months were dominated by absorbing type of aerosols whereas summer time scattering aerosols dominates the AOD values. Both winter and pre monsoon months do not shows large diurnal variations at the station.

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Abstract

In the present paper, MODIS (Terra and Aqua; level 2, collection 5) derived aerosol optical depths (AODs) are compared with the ground-based measurements obtained from AERONET (level 2.0) and Microtops - II sun-photometer over a tropical urban station, Pune (18°32'N; 73°49'E, 559 m amsl). This is the first ever systematic validation of the MODIS aerosol products over Pune. Analysis of the data indicates that the Terra and Aqua MODIS AOD retrievals at 550 nm have good correlations with the AERONET and Microtops - II sun-photometer AOD measurements.

During winter the linear regression correlation coefficients for MODIS products against AERONET measurements are 0.79 for Terra and 0.62 for Aqua; however for pre-monsoon, the corresponding coefficients are 0.78 and 0.74. Similarly, the linear regression correlation coefficients for Microtops measurements against MODIS products are 0.72 and 0.93 for Terra and Aqua data respectively during winter and are 0.78 and 0.75 during pre-monsoon. On yearly basis in 2008-2009, correlation coefficients for MODIS products against AERONET measurements are 0.80 and 0.78 for Terra and Aqua respectively while the corresponding coefficients are 0.70 and 0.73 during 2009-2010. The regressed intercepts with MODIS vs. AERONET are 0.09 for Terra and 0.05 for Aqua during winter whereas their values are 0.04 and 0.07 during pre-monsoon. However, MODIS AODs are found to underestimate during winter and overestimate during pre-monsoon with respect to AERONET and Microtops measurements having slopes 0.63 (Terra) and 0.74 (Aqua) during winter and 0.97 (Terra) and 0.94 (Aqua) during pre-monsoon.

Wavelength dependency of Single Scattering Albedo (SSA) shows presence of absorbing and scattering aerosol particles. For winter, SSA decreases with wavelength with the values 0.86 ± 0.03 at 440 nm and 0.82 ± 0.04 at 1020nm. In pre-monsoon, it increases with wavelength (SSA is 0.87 ± 0.02 at 440nm; and 0.88 ± 0.04 at 1020 nm).

1 **1. Introduction**

2 The knowledge of spatial and temporal distributions of aerosols on regional and
3 global scale is essential to understand the dynamics of aerosols and the associated
4 influence on regional and global climatic conditions (Tripathi et al., 2005). Satellites-
5 based remote sensing technique provides systematic retrieval of aerosol optical properties
6 on regional and global scale (Kaufman et al., 2005, Kahn et al., 2010). The MODerate
7 Resolution Imaging Spectroradiometers (MODIS) aboard the Terra (launched in 1999)
8 and Aqua (in 2002) observe the earth-atmosphere systems twice daily. Columnar aerosol
9 optical properties such as aerosol optical depth (AOD) and aerosol small mode fraction
10 (ASMF) are retrieved from these observations over both land and ocean (Kaufman et al.,
11 1997; Tanre et al., 1997). Satellite observations have advantages that they can provide
12 information in the larger spatio-temporal domain (Kaufman et al., 2002) as most of the
13 ground measurements are limited to very small area (point observations). However,
14 aerosols from the space is challenging in areas where surface reflectance is high as it may
15 introduce considerable errors in the derived results. So as to improve the accuracy of the
16 MODIS data, it is essential to compare and validate the MODIS data with independent
17 ground-based measurements. Several research studies have compared and validated
18 MODIS data with the data obtained from the ground-based Microtops II sun –
19 photometers and that measured from federated network instruments viz., Aerosol
20 Robotic Network (AERONET) (Jing-Mei et al., 2010; Retalis et al., 2010; Aloysus et al.,
21 2009; Misra et al., 2008; Levy et al., 2010; Remer et al., 2005; Tripathi et al., 2005;
22 Ichoku et al., 2002a; Chu et al., 2002; Holben et al., 1998, Hyer et al., 2011). Since the

23 launch of MODIS, validation studies suggested that the expected error (EE) over land
24 could be represented by $EE = \pm 0.05 \pm 0.15 \times AOD$ (Remer et al., 2005).

25 In India, several validation of MODIS derived AOD has been carried out by
26 various groups (Jethva et al., 2005, Tripathi et al., Prasad and Singh, 2007). Tripathi et
27 al., (2005) using MODIS level 2 and collection 4 AOD data with AERONET data for
28 2004 found an overestimation by MODIS during dust and an underestimation during non-
29 dust seasons having slopes and intercepts in the two cases 2.46, -0.63 and 0.69, 0.12
30 respectively with nearly same correlation coefficients (0.72 and 0.71 respectively). For
31 the Indo-Gangatic basin, Jethva et al.,(2005) compared the monthly mean AOD at 550
32 nm from MODIS level 3 daily gridded data with AERONET sunphotometer derived
33 monthly mean AOD values for Kanpur, India during January 2001 to July 2003 and
34 found a systematic overestimation by MODIS during summer and underestimation
35 during winter. Prasad and Singh (2007) also found MODIS overestimating AOD values
36 during summer and underestimating during winter with the slopes and intercepts with two
37 cases 0.51, 0.52 and 0.48, 0.15 respectively. The correlation coefficients in the two cases
38 were less than 0.5.

39 In the present study, we compare MODIS (Terra and Aqua) AOD retrievals with
40 AERONET AODs of level 2.0 and Microtops II sun-photometer measurements at Pune
41 ($18^{\circ}32'N$; $73^{\circ}49'E$, 559 m amsl), India. CIMEL sun-sky radiometer installed at Indian
42 Institute of Tropical Meteorology (IITM) as a part of AERONET global network, and it
43 makes measurements at 440, 675, 870, 940, and 1020nm and three polarized channels at
44 870 nm. In the present study, data retrieved from 440, 675, 870 and 1020 channels are
45 used The Microtops II sun-photometer (five channels) is operated from Pune University

campus on cloud free days observing seasons spanning over Dec-May for the period 2008-09 and 2009-10. To the best of our knowledge this is the first kind of systematic study that validates MODIS data over Pune. The study also presents seasonal behaviour of AERONET inversion products viz., aerosol columnar volume size distribution (ACVSD), single scattering albedo (SSA), and Angstrom Exponent (α).

2. Study Location and Local Meteorology:

The study location, over which the validation has been performed, is Pune ($18^{\circ}32'N$; $73^{\circ}49'E$, 559m amsl). It is about 100 km from the west coast of India and Lee-ward side of Sahyadri Range (Western Ghats). Pune has tropical wet and dry climate. Figure (1) shows the NCEP /NCAR reanalysis mean vector wind composites at 850 hPa for winter and pre-monsoon seasons during 2009 and 2010 over the Indian region ($0 - 40^{\circ}N$; $60 - 100^{\circ}E$). In winter (Dec, Jan and Feb), minimum temperature is up to 3 to $4^{\circ}C$ with light winds and continental air mass passing over the region. During the Pre-monsoon (Mar, Apr and May) the weather is very hot with the maximum temperature of about $40^{\circ}C$ and surface winds mostly gusty and dust content in the atmosphere is maximum.

The study region mainly comprises of semi arid region and has six types of land use and land cover as shown in Figure (2). It mainly consist of fallow land (39.42%), dense scrub (20.88%), agriculture land (15.96%), settlement (13.02%), vegetation (9.51%) and water body (1.18%). It contains 377 villages and has a population of 44,54,509 (Census of India 2001). The population and the number of vehicles and industrialization has been increasing at a steady rate over pune since 2001.

68 **3. Data and Methodology:**

69 **3.1 Data**

70 MODIS data are available at different processing levels, level 1.0 (geolocated &
71 calibrated brightness temperatures and radiances), level 2.0 (derived geophysical data
72 products) and level 3.0 (Gridded time-averaged product) (King et al., 2003). AERONET
73 data are also available at three different levels, level 1.0 (raw or unscreened data), level
74 1.5 (cloud screened data) and level 2.0 (quality assured data) (Holben et al., 1998). For
75 this study, we have employed MODIS (both Terra & Aqua) level 2 collection 5
76 instantaneous AOD data at 550 nm.. MODIS AOD retrievals are compared with level 2.0
77 AERONET and Microtops II sun-photometer measurements of AODs.

78 **3.2 MODIS**

79 Radiant energy reflected and emitted by the Earth carries a signature of atmospheric and
80 surface properties. Satellite sensors can quantify several atmospheric properties by
81 measuring the wavelength, angular and polarization properties of this radiant energy
82 (Kaufman et al., 2002). The MODIS has been designed with aerosol and cloud remote
83 sensing in mind (King et al., 1992). It is sun-synchronous and near polar orbiting, with a
84 circular orbit of 705 km above the surface. MODIS has 36 bands ranging from 0.4 to 14.4
85 μm wavelengths with three different spatial resolutions (250, 500 and 1000 m) and views
86 the Earth with a swath of 2330 km thereby observing the entire globe every day, with
87 equatorial crossing local time 10:30 am and 1:30 pm (Terra and Aqua respectively).

88 The MODIS retrievals of aerosol use two separate algorithms for land and ocean.
89 Both the algorithms were developed before the Terra launch and are well described in

90 Kaufman et al. (1997) for land and Tanre et al. (1997) for ocean. MODIS retrievals of
91 AOD over land uses three spectral channels centered at 0.47, 0.66, and 2.13 μm
92 wavelength. The retrieval of AOD is performed and reported at $10 \times 10 \text{ km}^2$ pixel size
93 although the original observations are made at 250-1000m resolution. Each high
94 resolution pixel in the $10 \times 10 \text{ km}^2$ box is evaluated for cloud, ice/snow and then mean
95 reflectance values are utilized to retrieve AOD using lookup table approach. More details
96 on AOD retrieval can be found elsewhere [i.e. Remer et al., 2005, Levy et al., 2007a,
97 2007b]

98 **3.4 AERONET (AErosol RObotic NETwork)**

99 The AERONET (AErosol RObotic NETwork) is a federation of ground-based
100 remote sensing aerosol networks established by NASA and is greatly expanded by
101 collaborators from other agencies. The program provides a long-term, continuous
102 database of aerosol optical, microphysical and radiative properties for aerosol research
103 and characterization, validation of satellite retrievals, and synergism with other databases.
104 The network imposes standardization of instruments, calibration, processing and
105 distribution.

106 AERONET provides globally distributed observations of spectral AOD, inversion
107 products, and precipitable water in various aerosol regimes. It employs CIMEL sun-sky
108 spectral radiometer which measures the direct sun radiances at eight spectral channels
109 centered at 340, 380, 440, 500, 670, 870, 940 and 1020 nm. The accuracy of direct sun
110 measurements are within ± 0.01 and ± 0.02 for larger wavelengths (greater than 440 nm)
111 and shorter wavelength (Holben et al., 1998; Eck et al., 1999). Optical depth is calculated
112 from spectral extinction of direct beam radiation at each wavelength based on the

113 Lambert-Beer-Bouguer Law. Aerosol optical depth (AOD) is determined by correcting
114 optical depth for attenuation due to Rayleigh scattering, absorption by ozone and gaseous
115 pollutants. In addition to direct solar radiance, instrument also measures the diffuse sky
116 radiance at four spectral bands (440, 670, 870 and 1020 nm) along the solar principal
117 plane and solar almucantar through a constant aerosol profile to retrieve size distribution,
118 phase function and AOD (Holben et al., 1998).

119 Indian Institute of Tropical Meteorology (IITM) is one of the stations of this
120 network. CIMEL sun/sky radiometer is installed in the campus of IITM and continuously
121 operational since 2004 (Sumit and Devara, 2011). The automatic sun-sky tracking
122 radiometer at IITM makes measurements with a 1.2° full field of view at every ~15 min
123 interval at five spectral channels (440, 675, 870, 940, 1020nm). In this study data
124 retrieved from 440, 675, 870 and 1020 nm are used for its comparison with MODIS AOD
125 retrievals. To determine aerosol columnar volume size distribution and Single Scattering
126 Albedo (ω_0) solar principal plane (constant azimuth angle, with varied scattering angles)
127 and solar almucantar (constant elevation angle, with varied azimuth angles) geometry is
128 used at 440, 675, 870 and 1020 nm.

129 **3.5 Microtops II Sun-photometer**

130 The ground based measurements have been carried out at Pune University campus
131 ($18^\circ 32'N$; $73^\circ 49'E$) using handheld Microtops II Sun-photometer from morning till
132 evening at an interval of 10 min. during 2008-09 and 2009-10 on clear sky days. The
133 instrument is well calibrated (Manufactured by Solar Light Company, Philadelphia,
134 USA.). The design, calibration and performance details have been described by Devara et
135 al., (2001) and Morys et al., (2001). The expected accuracy of the sun-photometer

136 retrievals is comparable with those of CIMEL sun-photometer used in AERONET
137 network with uncertainties in the range of 0.01 to 0.02 (Ichoku et al., 2002b). The
138 instrument measures the intensity of direct solar irradiance at five spectral narrow band
139 spectral channels centered at 440, 500, 675, 870 and 1020 nm. From this data, AOD
140 value for each wavelength is estimated. These data are used along with AERONET as a
141 “ground truth” for the validation of the MODIS AOD products for this study.

142 **3.6 Methodology**

143 For validation purpose, MODIS retrievals must be collocate in space and time with
144 AERONET and Microtops measurements. We averaged the quality controlled MODIS
145 AOD values at 10 km² spatial resolution over 50 km × 50 km grid box centered at ground
146 measurements site. For this, we choose 50 km × 50 km grid box because in larger
147 window size, topography and aerosol type heterogeneity play a role and could bring in
148 errors where as smaller grid box contain insufficient data (Ichoku et al., 2002a).

149 In order to accomplish realistic comparison of AOD’s from these instruments viz.,
150 MODIS, AERONET and Microtops II sun-photometer. AERONET and Microtops
151 measured AODs are adjusted to the MODIS derived 550 nm wavelength AODs using the
152 Angstrom exponent (α) and Angstrom turbidity coefficient (β) derived from Microtops
153 and AERONET measured AODs at the wavelengths 440, 500, 675, 870 and 1020 nm
154 (440, 675, 870 and 1020 nm for AERONET) on the corresponding day through a
155 logarithmic regression using the Angstrom empirical formula viz., $AOD = \beta \times \lambda^{-\alpha}$. This
156 yields the corresponding retrieved AOD value at 550 nm for the AERONET and
157 Microtops within ± 30 min of MODIS overpass time. Thus, over the two years period (i.e.
158 2008-09 and 2009-10), we obtained 118 and 119 identical data sets for MODIS (Terra)

159 and AERONET (48 and 60 data sets for Microtops) during 2008-09 and 2009-10
160 respectively. Similarly, there were 101 and 96 identical data points for MODIS (Aqua)
161 and AERONET (41 and 50 data points for Microtops) during the same period. Thus
162 MODIS -AERONET and MODIS – Microtops data sets form the subject matter of the
163 present paper.

164 **4 Results and Discussion**

165 **4.2 Aerosol Properties**

166 **4.2.1 AOD Variation and Angstrom Exponent (α)**

167 The spectral variation of aerosol optical depth and frequency distribution of α
168 during winter and pre-monsoon season for the period of Dec 2008-May 2010 over Pune
169 is shown in Figure 3(a b). Seasonal variation of α is monomodal in winter and bimodal
170 in pre-monsoon. The modal value of α of 1.4 during winter suggests dominance of
171 submicron aerosol particles originating from anthropogenic activity like fossile fuel
172 combustion and biofuel burning (Pandithurai et al., 2007, Venkataraman et al., 2005,).
173 During pre-monsoon, bimodal nature of α has modal values 0.5 and 0.95 indicating that
174 dominance of both fine and coarse mode particles. This reveals that the aerosol system
175 over Pune is controlled by different sources.

176 Figure (4) reveals monthly mean value of aerosol optical depth and α obtained from
177 AERONET measurements during Dec2008-May2010. From the figure, high AE values at
178 low AODs during winter and low α at high AOD values during pre-monsoon also
179 indicates the dominance of fine mode and coarse mode particles in winter and pre-
180 monsoon respectively.

181 4.2. 2 Aerosol Columnar Volume Size Distribution

182 Atmospheric aerosols, which come from many natural and man-made sources,
183 present a wide range of particle sizes and concentrations. Their behavior and the
184 atmospheric effects produced by them depend on their size. The inversion algorithm
185 developed by Dubovik and King (2000) has been used.

186 Results of this analysis are given in Figure (5) which depicts seasonal variation of
187 aerosol columnar volume size distribution over Pune using AERONET data during the
188 period Dec 2008 – May 2010. It is clear from the figure that the modal volume size
189 concentration of both accumulation mode ($< 1 \mu\text{m}$) and coarse mode ($> 1 \mu\text{m}$) are low
190 during winter. As compared to winter, during pre-monsoon there is no considerable
191 change in accumulation mode but there is significant increase in modal volume
192 concentration (about 1.5) for the coarse mode. The dominance of coarse mode particles
193 may be due to dust generation by strong winds (wind blown dust) and strong surface
194 heating. Low value of α (0.85) also supports the dominance of coarse mode particles in
195 pre-monsoon. The sources of fine mode particles are fossil fuel combustion and industrial
196 pollutants.

197 The observed Aerosol Columnar Volume Size Distribution (ACVSD) is found to
198 be bimodal and is represented by

$$199 \quad \frac{dV}{d \ln r} = \frac{V_0}{\sigma(2\pi)} \exp\left(-\frac{\ln[r/r_m]^2}{2\sigma^2}\right) \quad (1)$$

200 where $dV/d \ln r$ is volume size distribution, V_0 is columnar volume of particle per cross
201 section of atmosphere, r is radius, r_m is mode radius and σ is standard deviation of the
202 natural logarithm of particle radii.

203 The bimodal nature of volume size distribution may be due to different sources of
204 aerosols such as combination of two air masses with different aerosol origin (Hoppel et
205 al., 1985), generation of new fine particles in the air by the process of heterogeneous
206 nucleation or by homogeneous heteromolecular nucleation and growth of larger particles
207 by condensation of gas-phase reaction products (Singh et al., 2004).

208 The ACVSD parameters and α are given in Table I. During winter, the average values of
209 volume concentration of accumulation mode and coarse mode are 0.020 ± 0.016 and
210 0.025 ± 0.017 respectively and in pre-monsoon, the corresponding average values are
211 0.022 ± 0.015 and 0.047 ± 0.032 . For accumulation mode, the model value of volume
212 concentration (peak) is almost same (0.046 and 0.044) for winter and pre-monsoon
213 respectively. For coarse mode, values of volume concentration are 0.053 and 0.087 for
214 winter and pre-monsoon respectively.

215 **4.2.3 Single Scattering Albedo**

216 Single scattering albedo (SSA) is a common measure of the relative contribution of
217 absorption to extinction and is a key variable in assessing the climatic effects of aerosols
218 (Jacobson, 2000; Dubovik et al., 2002). Its value is mostly dependent on the composition
219 and size distribution of aerosols. It is studied by using AERONET inversion product
220 (level 2.0) during Dec 2008 to May 2009. For this, the retrieval algorithm of Dubovik and
221 King (2000) is used to obtain SSA from direct sun and sky radiance measurements by
222 AERONET (CIMEL sun photometer).

223 Figure (6) depicts the wavelength dependence of SSA. During winter, SSA decreases
224 with wavelength having a value 0.86 ± 0.03 at 440 nm and 0.82 ± 0.04 at 1020 nm. Lower

SSA at longer wavelength shows dominance of absorbing urban aerosol over Pune, which is attributed to the presence of a mixture of aerosols from multiple sources like vehicular pollution, industrial pollutants, biomass burning in the field. However, in pre-monsoon season, the SSA slightly increases with wavelength (SSA is 0.87 ± 0.02 at 440nm; and 0.89 ± 0.04 at 1020 nm). This suggests the dominance of coarse particles (mostly dust) during pre-monsoon, which may be either due to local activities like urbanization, industrialization and construction activities or windblown dust due to strong surface heating. Similar observations have been reported by Singh et al., (2004) over Kanpur, Smirnov et al., (2002) in the Persian Gulf, Xia et al., (2005) and Cheng et al., (2006) over Northern China and Lyamani et al. (2006) over Europe and the Mediterranean region. Monthly variation of SSA for the period of 2008-10 and 2009-10 is shown in Figure (7). It reveals that during 2008-09 there is a sharp increase in SSA from Dec to May while the increase is moderate during 2009-10. Seasonal variation and spectral dependence of SSA is well reflected in the monthly variation.

4.3 Inter-comparison between MODIS-AERONET-Microtops II Sun-photometer

4.3.1 MODIS and AERONET

Figure (8) shows seasonal comparison of MODIS AOD retrievals against AERONET derived AODs, during the winter (Dec-Feb, 2008-2010) and pre-monsoon (Mar-May, 2009-2010). From the figure, it is seen that during winter the correlation coefficient of linear regression fit (R) are 0.79 and 0.62 for Terra and Aqua respectively. While during pre-monsoon the corresponding coefficients are 0.78 and 0.74. These correlation coefficients are significant at 0.01 level. The root mean squared error (RMSE)

247 between the ground based AERONET and MODIS AODs lies in the range 0.09 to 0.10
248 for the data under study.

249 Intercepts of linear regression fit are 0.09 for Terra and 0.05 for Aqua during
250 winter whereas during pre-monsoon intercept values are 0.04 and 0.07 for Terra and
251 Aqua respectively. Slopes of the regressed lines, for Terra and Aqua are 0.63 and 0.74
252 respectively during winter and 0.97 and 0.94 (for Terra and Aqua respectively) during
253 pre-monsoon.

254 Results of regression model for MODIS derived AODs against AERONET
255 measurements at 550 nm during 2008-2009 and 2009-2010 are shown in Table II. It is
256 clear from the table that during 2008-2009 and 2009-2010, MODIS retrievals bear a good
257 correlation with AERONET measurements with correlation coefficients 0.80 and 0.78 for
258 (Terra and Aqua respectively) during 2008-2009 while the corresponding coefficients are
259 0.70 and 0.73 during 2009-2010. Intercept of linear regression model during 2008-2009
260 are 0.05 and -0.01 for Terra and Aqua respectively and the corresponding intercept
261 during 2009-2010 is 0.11 for both Terra and Aqua. Slopes of the regressed line are 0.86
262 and 1.05 during 2008-2009 for Terra and Aqua respectively while during 2009-2010, the
263 corresponding slopes are 0.65 and 0.73.

264 **4.3.2 MODIS and Microtops II Sun-photometer**

265 Figure (9) shows scatter plot of MODIS AOD retrievals against Microtops
266 measured AODs, during the winter (Dec-Feb, 2008-2010) and pre-monsoon (Mar-May,
267 2008-2010). MODIS AOD retrievals also show a good correlation with Microtops II sun-
268 photometer measurements. Correlation coefficients during winter are 0.73 and 0.93 while
269 for pre-monsoon values are 0.78 and 0.75, for Terra and Aqua respectively. RMSE

270 between ground based Microtops II sun-photometer and MODIS AODs lie in the range
271 0.06 – 0.10 for winter and pre-monsoon during the study period.

272 Intercepts of the linear regression fit for MODIS and Microtops AODs are 0.03
273 for Terra and 0.04 for Aqua during winter whereas for pre-monsoon, intercept values are
274 0.05 and 0.09 for Terra and Aqua respectively. Slopes of the regressed lines are 0.54 &
275 0.70 during winter and 0.58 & 0.76 during pre-monsoon for Terra and Aqua respectively.

276 **4.3.3 AERONET and Microtops II Sun-photometer**

277 Figure (10) reveals the scatter plot of AERONET against Microtops at 675nm for all
278 collocated data points during 2008-2010. The linear regression analysis between these
279 data points shows that the correlation coefficient is 0.81 while slope and intercept are
280 0.97 and 0.10 respectively. The seasonal inter-comparison between AERONET and
281 Microtops is shown in Figure (11). It is clear from the Figures (10 and 11) that,
282 Microtops AODs are consistently overestimating compared to those of the AERONET
283 AODs during winter and pre-monsoon over the study period with mean bias is about 0.1
284 in AOD.

285 From the Figures 8 and 9 it is clear that, the MODIS retrievals systematically
286 underestimate during winter and overestimate during pre-monsoon over Pune. Similar
287 results have been reported by Jethva et al.,(2005) and Prasad and Singh (2007) over
288 Kanpur. Monthly variation of AOD using MODIS and AERONET measurements shown
289 in Figure (12) also support this result.

290 The linear regression model for MODIS-AERONET (Fig. 8) and MODIS-Microtops II
291 (Fig 9) and Table II show non-zero intercepts. This indicates that the retrieval algorithm

292 is biased at low AOD values which may be associated with a sensor calibration error or
293 an improper assumption about ground surface reflectance (Tripathi et al., 2005; Zhao et
294 al., 2002). Also, large errors in surface reflectance may lead to large intercepts (Tripathi
295 et al., 2005; Chu et al., 2002).

296 The inconsistency between aerosol microphysical and optical properties used in the
297 MODIS retrieval algorithm and that in the ground truth retrievals generated by
298 AERONET and Microtops is signified by the deviation of the slope from unity. Similar
299 observations have been reported by in other studies (i.e. Jing-Mie , 2010; Tripathi et al.,
300 2005; Zhao et al., 2002).

301 The effect of slope and intercept on the correlation of MODIS derived AODs with
302 AERONET and Microtops measurements shown in Figure (8) and Figure (9) is well
303 represented in the average monthly variation of AOD values from MODIS and
304 AERONET during the study period (2008-10) as shown in Figure (12). Error bars in the
305 figure represent standard deviation of AOD in the month which generally ranges between
306 0.05 - 0.2. The number of days used in the analysis is also indicated on bar chart. It is
307 clear from the figure that the variation patterns of both MODIS (Terra and Aqua) and
308 AERONET AOD data are well matched for both the years with MODIS AOD values
309 relatively lower than those of AERONET AOD values in winter i. e. in relatively low
310 dust period. While in dust loading period (pre-monsoon), MODIS AOD values are higher
311 or tend to be higher than the AERONET AODs. Similar observations have been reported
312 by Tripathi et al., (2005).

313 As overpass time of MODIS Terra and Aqua are 10:30 and 1: 30 respectively the
314 monthly variation of AERONET-Microtops-MODIS-Terra data sets corresponds to

315 monthly variation of AOD during morning hours and that of AERONET-Microtop-
316 MODIS-Aqua to monthly variation of AOD during afternoon. This may be regarded as
317 the diurnal asymmetry in AOD data. This has its origin in the meteorological conditions
318 over Pune. Weather conditions in Pune in winter are conducive to the formation of low
319 level capped inversion of $8 - 10^{\circ}$ K per 100 meter in the atmospheric boundary layer
320 (ABL) during February and to some extent also in March. (Vernekar et al., 1993,
321 Pandhurai et al., 2007). High value of AOD in January/February for Terra and Microtop
322 is produced by the processes such as atmospheric moisture precipitating as haze particles
323 on cold mornings in winter, inversion episodes and the influx of aerosol due to
324 atmospheric circulation as discussed in NCEP/NCAR reanalysis mean vector wind
325 composites at 850 hPa for winter and pre-monsoon seasons (Figure 1). April/May
326 maximum in AOD is normal pre-monsoon high. High value of AOD in pre-monsoon is
327 also a global feature attributed to increased aerosol inputs due to surface heating, wind-
328 blown dust and influx of aerosols (Holben et al., 2001)

329 Seasonal frequency distribution for collocated data points of Terra and Aqua of
330 MODIS and AERONET measured values for 2008-09 and 2009-10 presented in Figure
331 (13). It is clear from the figure that, the frequency distribution is maximum at the range
332 $AOD < 0.3$ and $0.3-0.4$ during winter and pre-monsoon respectively. During winter in the
333 range of $AOD < 0.3-0.4$ the frequencies of MODIS AODs are higher than those of
334 AERONET AODs while during pre-monsoon reverse of this case can be seen clearly.
335 The frequencies of MODIS AODs during pre-monsoon found lower than those of
336 AERONET AODs at the range of $AOD < 0.3-0.5$. Maximum frequency difference is 5.86
337 % for winter and 7.04 % during pre-monsoon.

338 In the range of AOD > 0.5 MODIS AODs are consistently lower than AERONET
339 AODs during winter while in pre-monsoon in the AOD range > 0.6 MODIS AODs are
340 consistently higher than AERONET AODs. The frequency distribution pattern also
341 supports the underestimation of AOD by MODIS during winter and overestimation
342 during pre-monsoon.

343 **5. Summary and Conclusion**

344 The paper presents the comparison of MODIS AODs (Terra and Aqua) retrievals with
345 ground-based measurements made by AERONET and Microtops II sun-photometer for 2
346 years over a tropical urban station, Pune. The main conclusions from the study are:

- 347 1. Higher value of α during winter is associated with low AODs and an opposite
348 trend is found to prevalent during pre-monsoon. This confirms occurrence of fine
349 and coarse mode particles during these seasons.
- 350 2. Aerosol volume size distribution is shows a bimodal distribution during both
351 winter and premonsoon seasons. The volume concentration of coarse mode
352 particles in pre-monsoon is 1.5 times higher as compared to that winter. Similarly,
353 volume concentration of fine mode particles is nearly same in both winter and
354 pre-monsoon. Bimodal structure of volume size distributions indicates the
355 presence of a mixture of aerosols from multiple sources during respective seasons
356 in the atmosphere over Pune.
- 357 3. The SSA observer over Pune is found to be highly wavelength dependent. It
358 decreases with wavelength in winter indicating the dominance of absorbing
359 aerosols mainly arising from vehicular pollution, industrial pollutants and biomass

360 burning. During pre-monsoon an opposite trend is observed showing the presence
361 of coarse mode particles which may be due to construction activity, wind blown
362 dust and strong surface heating.

363 4. The MODIS AOD retrievals are well correlated with the AERONET and
364 Microtops measurements as indicated by the high correlation coefficients. These
365 are found to be 0.79 for Terra and 0.62 for Aqua during winter; 0.78 for Terra and
366 0.74 for Aqua during pre-monsoon against AERONET data. The corresponding
367 values for Microtops measurements are 0.72 for Terra and 0.93 for Aqua during
368 winter; 0.78 for Terra and 0.75 for Aqua during pre-monsoon with small
369 intercepts.

370 5. MODIS AODs underestimate during winter and overestimate during pre-monsoon
371 with respect to the AERONET and Microtops measurements with slopes less than
372 unity (0.63 for Terra and 0.74 for Aqua during winter; 0.97 for Terra and 0.94 for
373 Aqua during pre-monsoon against AERONET and 0.54 for Terra and 0.70 for
374 Aqua during winter; 0.58 for Terra and 0.76 for Aqua during pre-monsoon against
375 Microtops II sun-photometer).

376 6. Average monthly variation of AODs of MODIS and AERONET shows a similar
377 pattern of variation with MODIS AOD values systematically less than those of
378 AERONET during winter and higher during pre-monsoon. High AODs are
379 observed during January/ February and April/May. Jan/ Feb high is mainly due to
380 higher relative humidity during morning hours, light wind and associated low
381 level capped inversions in the morning. Higher AOD values in April/May are

382 associated with increased aerosol inputs due to surface heating, wind-blown dust
383 and influx of aerosols

384 7. Microtops AODs are consistently overestimating than those of AERONET AODs
385 during the study period with mean bias is about 0.1 in AOD.

386 8. Although, there is systematic error in the MODIS products which needs further
387 investigation. In spite of this, results presented in the present paper indicate that
388 the Terra and Aqua MODIS retrievals are capable of characterizing AOD
389 distributions over tropical urban region Pune.

390

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Table I: Observed seasonal columnar volume size distribution parameters of aerosol particles and Angstrom Exponent (α)

Season	V_a	R_a	σ_a	V_c	R_c	σ_c	α
Winter	0.047	0.148	0.025	0.053	3.857	0.028	1.307 (± 0.189)
Premonsoon	0.044	0.113	0.027	0.087	3.857	0.047	0.851 (± 0.315)

V is columnar volume of atmospheric aerosol particles per unit cross section of the atmospheric column, *R* is the radius and σ is standard deviation (subscripts “a” and “c” stands for accumulation mode and coarse mode respectively) and α is mean Angstrom Exponent.

Table II: Results of regression analysis for MODIS (Terra and Aqua) derived AOD against AERONET measurements at 550 nm during 2008-09 and 2009-10

Year		Slope	Intercept	R	RMSE	% in EE	N
2008-09	Terra	0.86	0.05	0.80	0.09	83.89	118
	Aqua	1.05	-0.01	0.78	0.10	73.26	101
2009-10	Terra	0.65	0.11	0.70	0.11	68.07	119
	Aqua	0.73	0.11	0.73	0.11	69.79	96

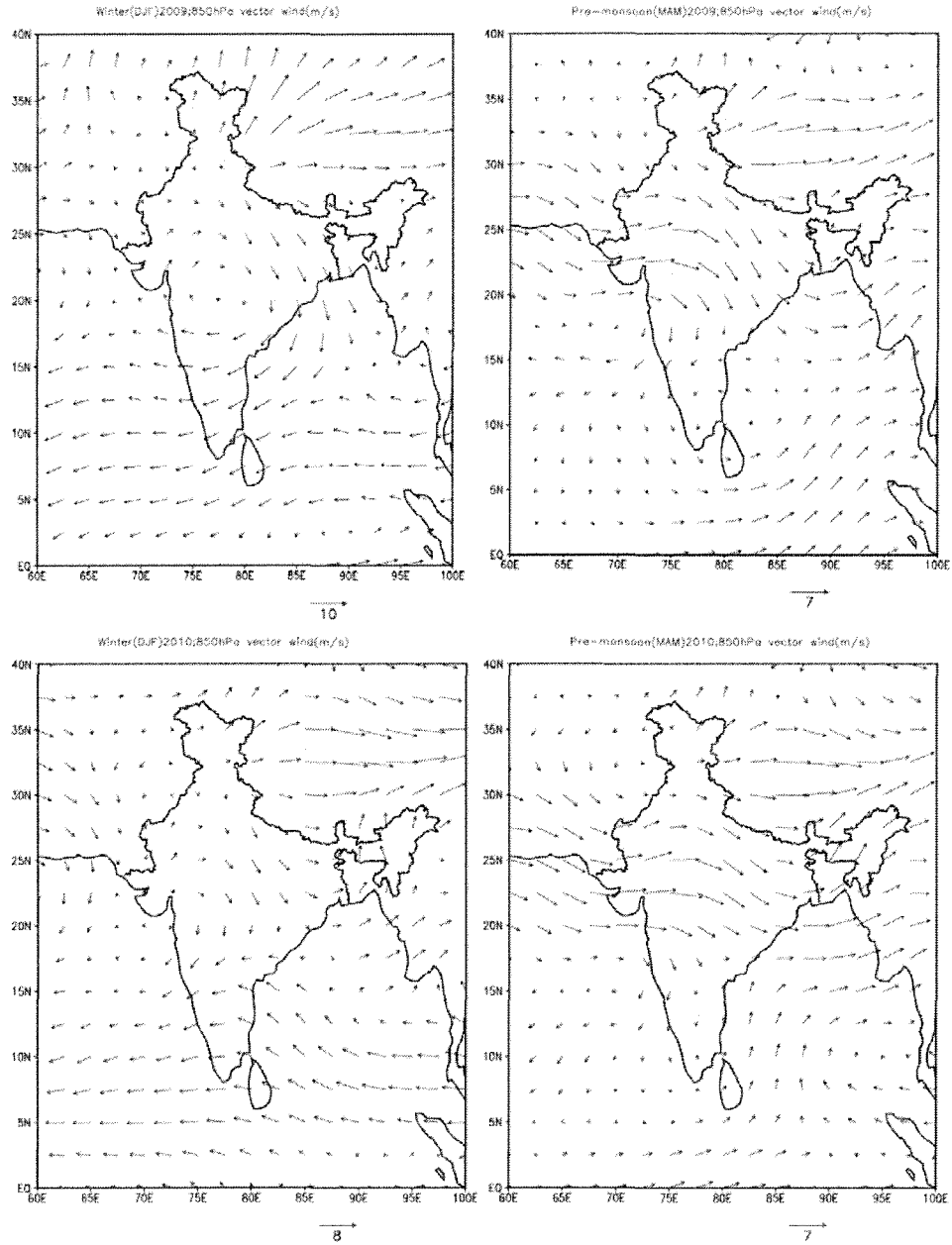


Figure 1:- NCEP /NCAR reanalysis mean vector wind composites at 850 hPa level for winter and pre-monsoon season during 2008-09 and 2009-10

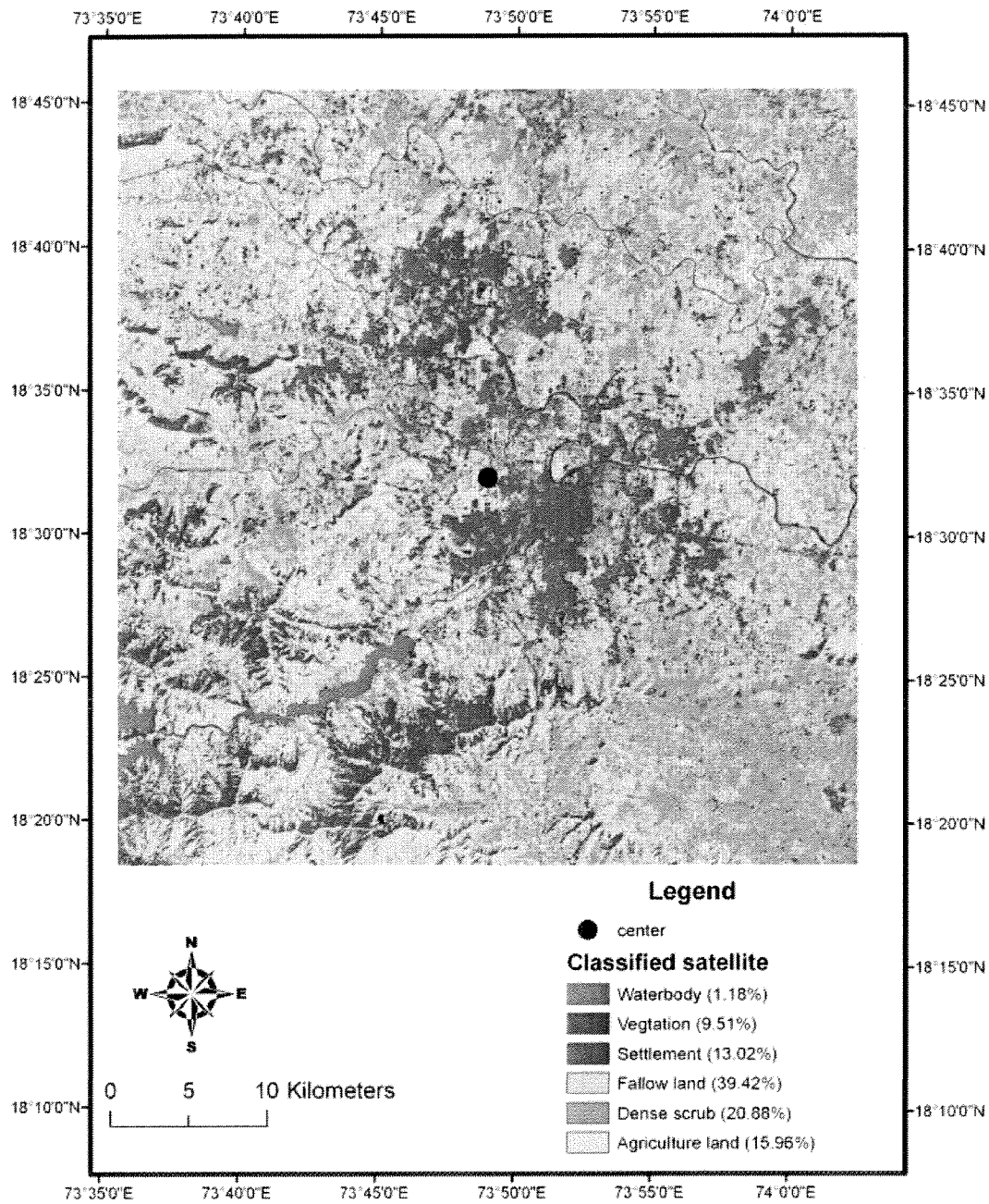


Figure 2: Land cover and land use of the study region (50 x 50 grid box)

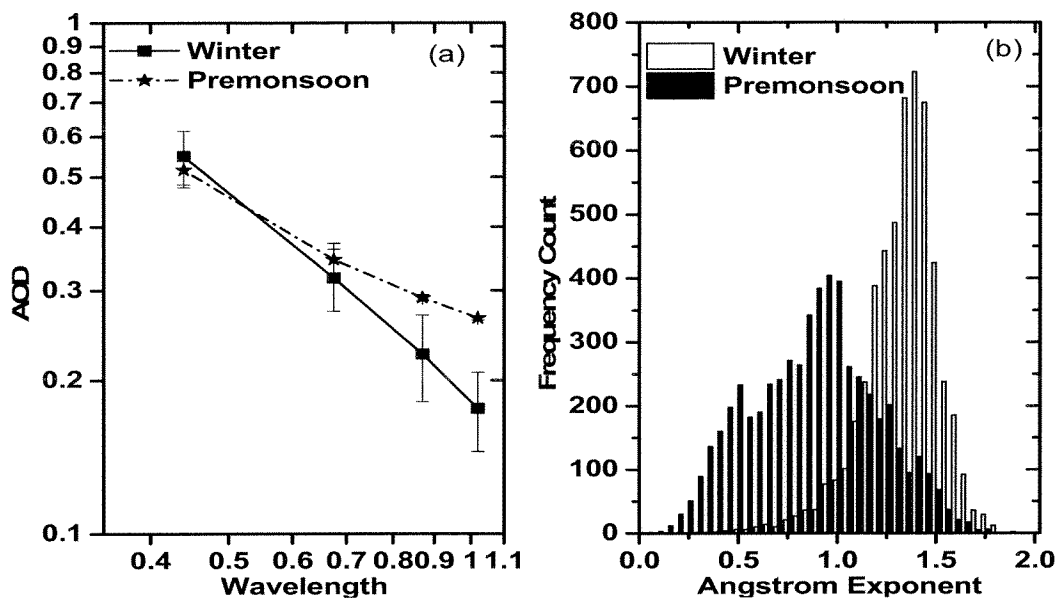


Figure 3: (a) Spectral variation of AOD and (b) frequency distribution of Angstrom exponent over Pune using AERONET measurements for the period Dec 2008 – May 2010.

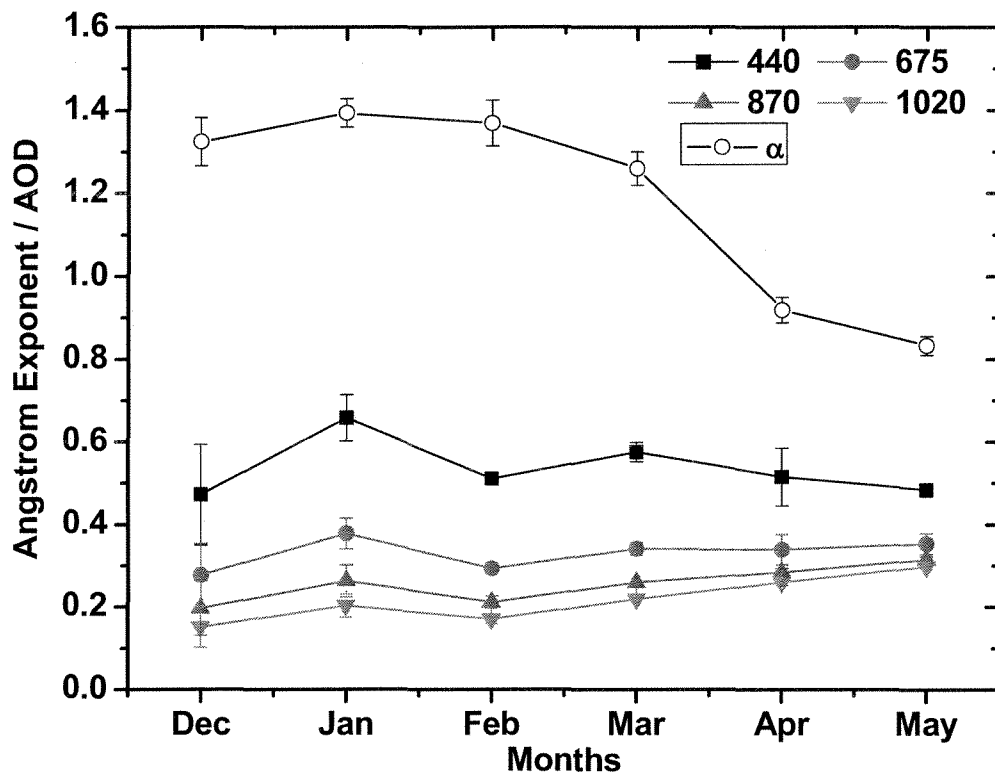


Figure 4: Monthly mean value of aerosol optical depth and Angstrom exponent (α) using AERONET data during Dec 2008-May 2010.

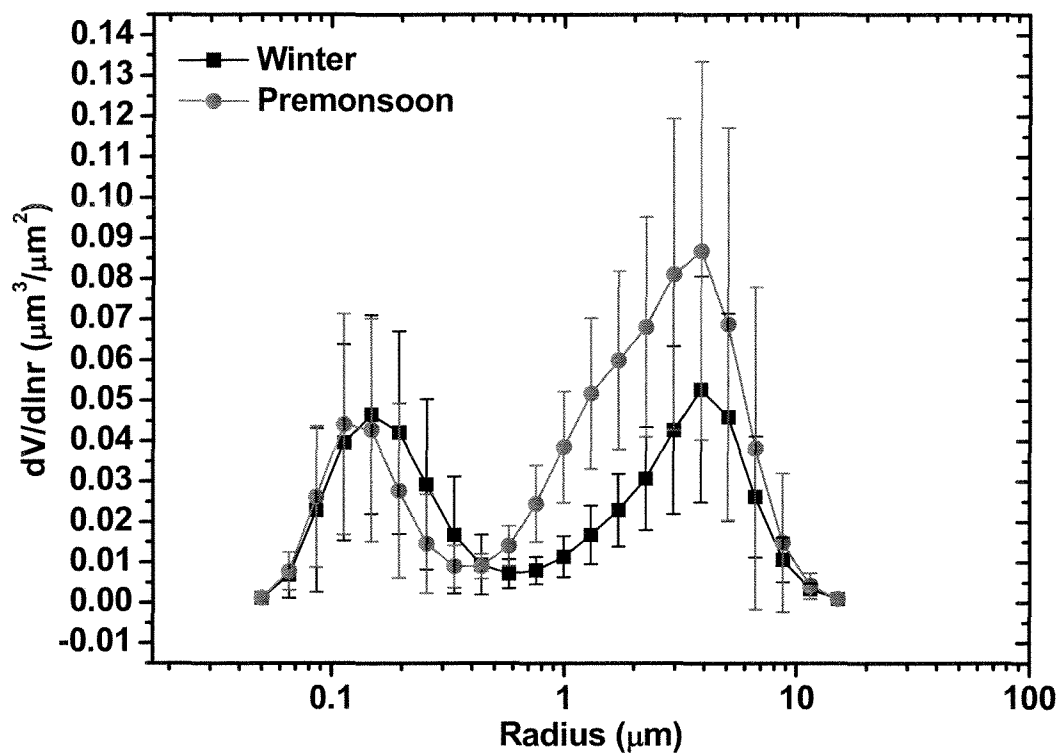


Figure 5: Seasonal variation of aerosol columnar volume size distribution over Pune using AERONET measurements during the period Dec 2008 – May 2010.

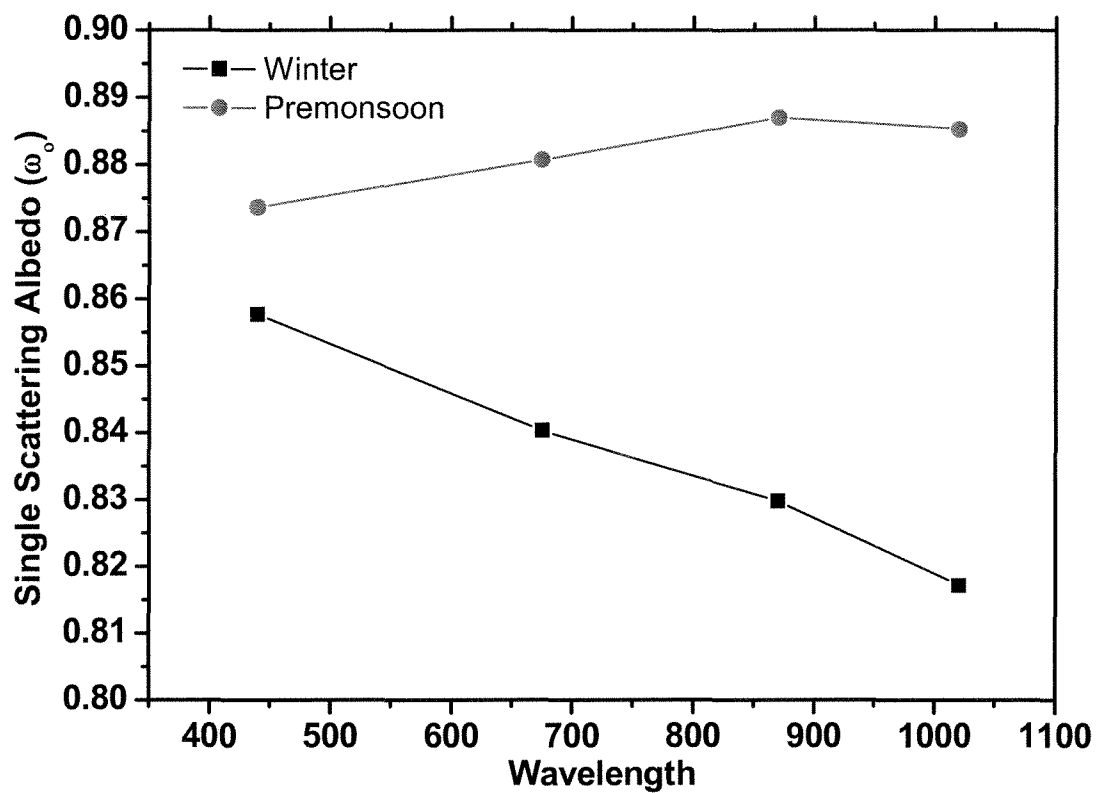


Figure 6: Wavelength dependency of single scattering albedo over Pune using AERONET measurements for the period Dec 2008 – May 2010.

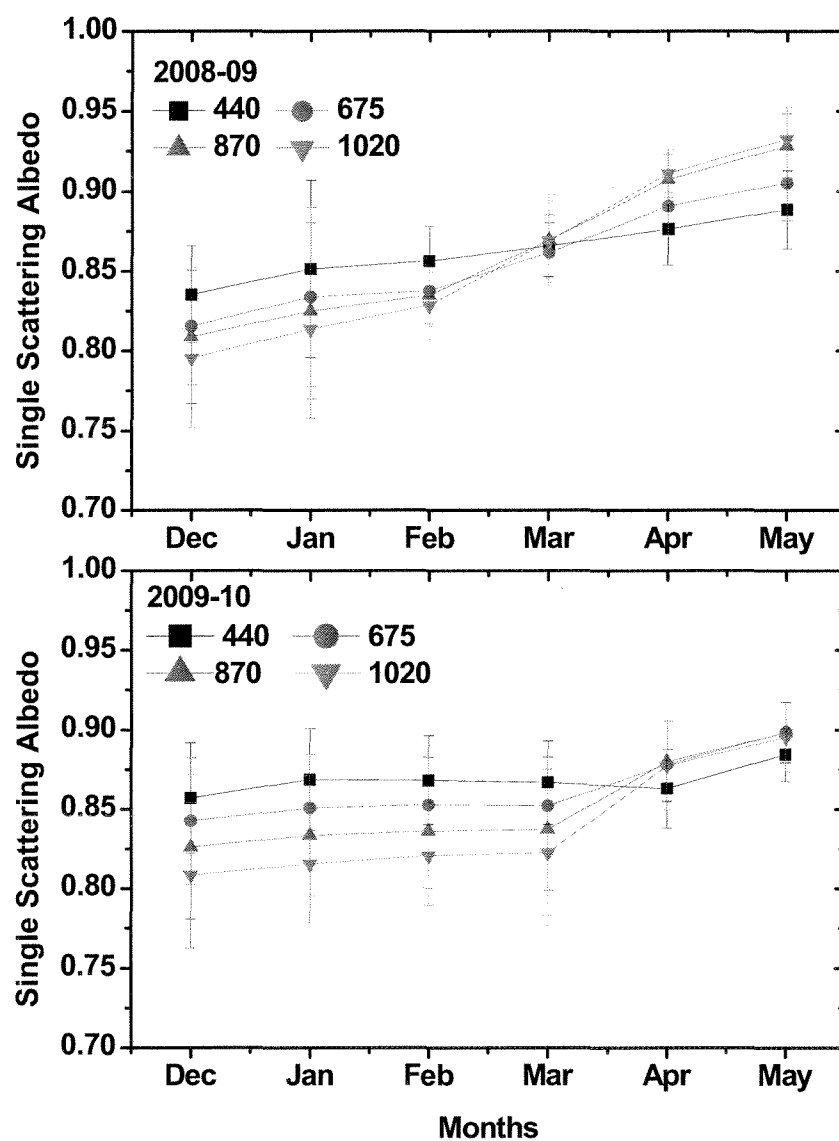


Figure 7: Monthly variation of single scattering albedo over Pune using AERONET measurements during 2008-09 and 2009-10.

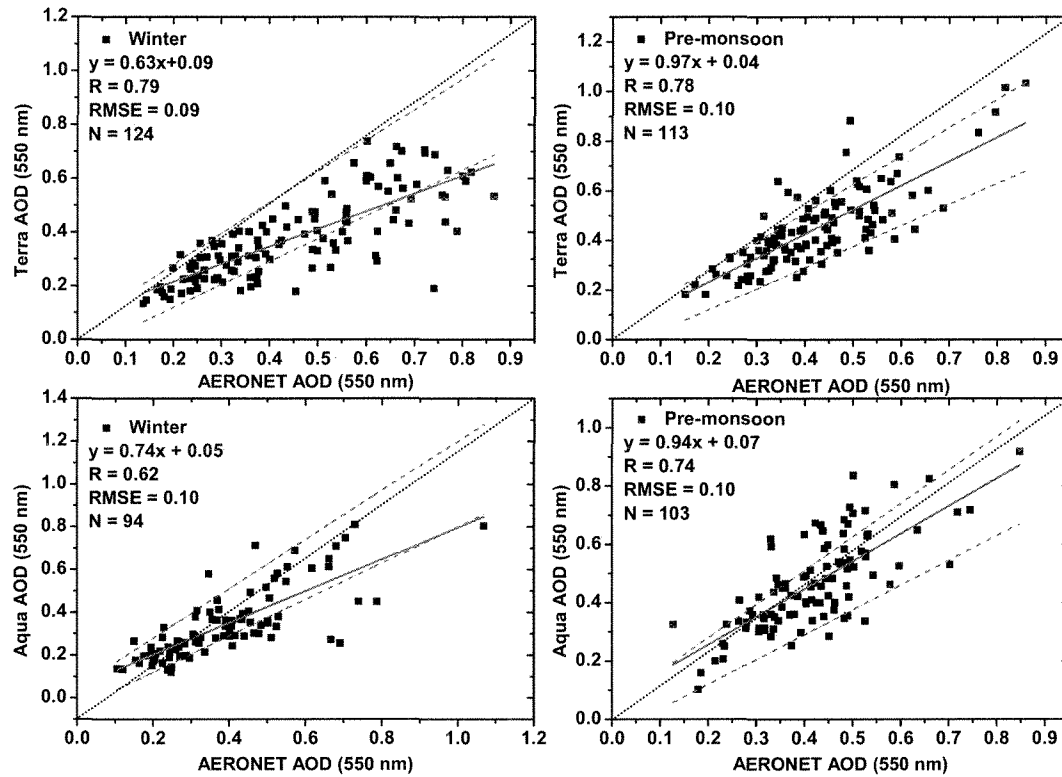


Figure 8: Scatter plots of MODIS (Terra and Aqua) AOD retrievals against AERONET derived AODs, during the winter and pre-monsoon during 2008-2010. (The thick solid lines, dashed lines and dotted lines represent linear regression, EE and 1:1 line respectively).

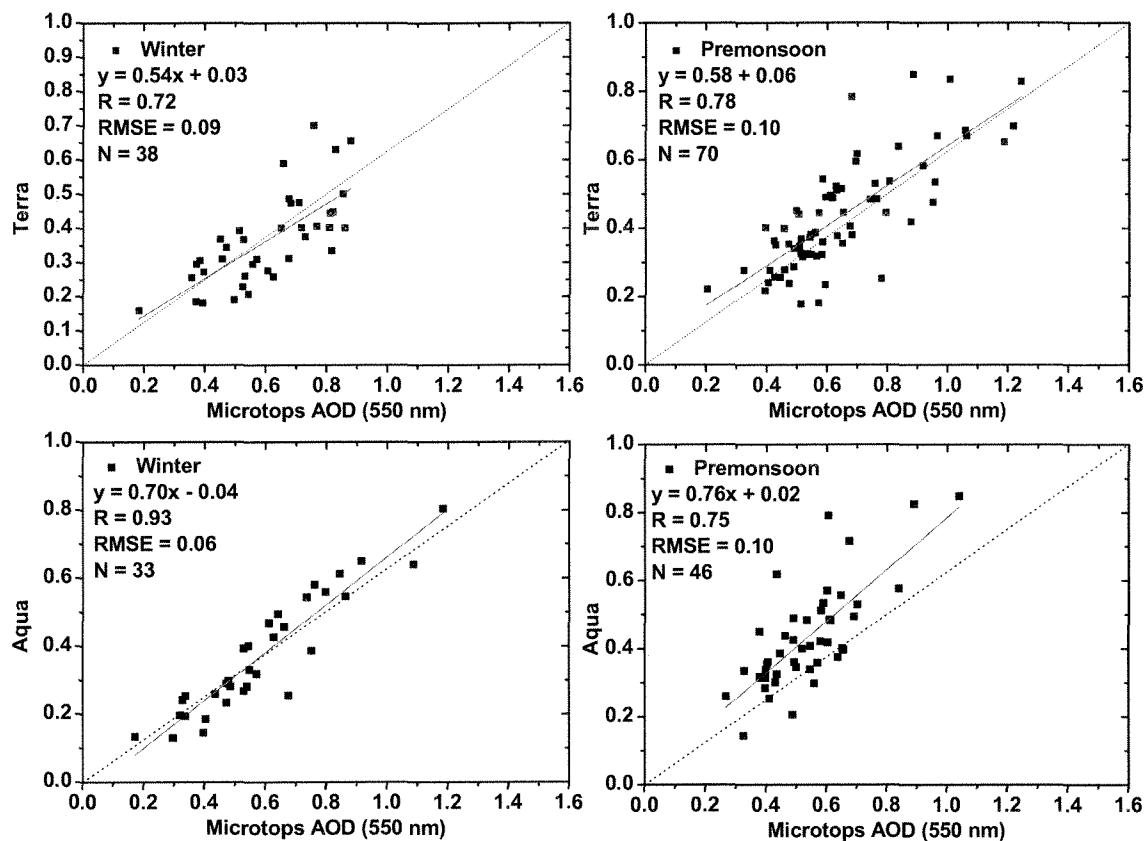


Figure 9: Scatter plots of MODIS (Terra and Aqua) AOD retrievals against Microtops measured AODs, during the winter and pre-monsoon during 2008-2010. (The solid lines represent linear regression and dotted lines are 1:1 lines).

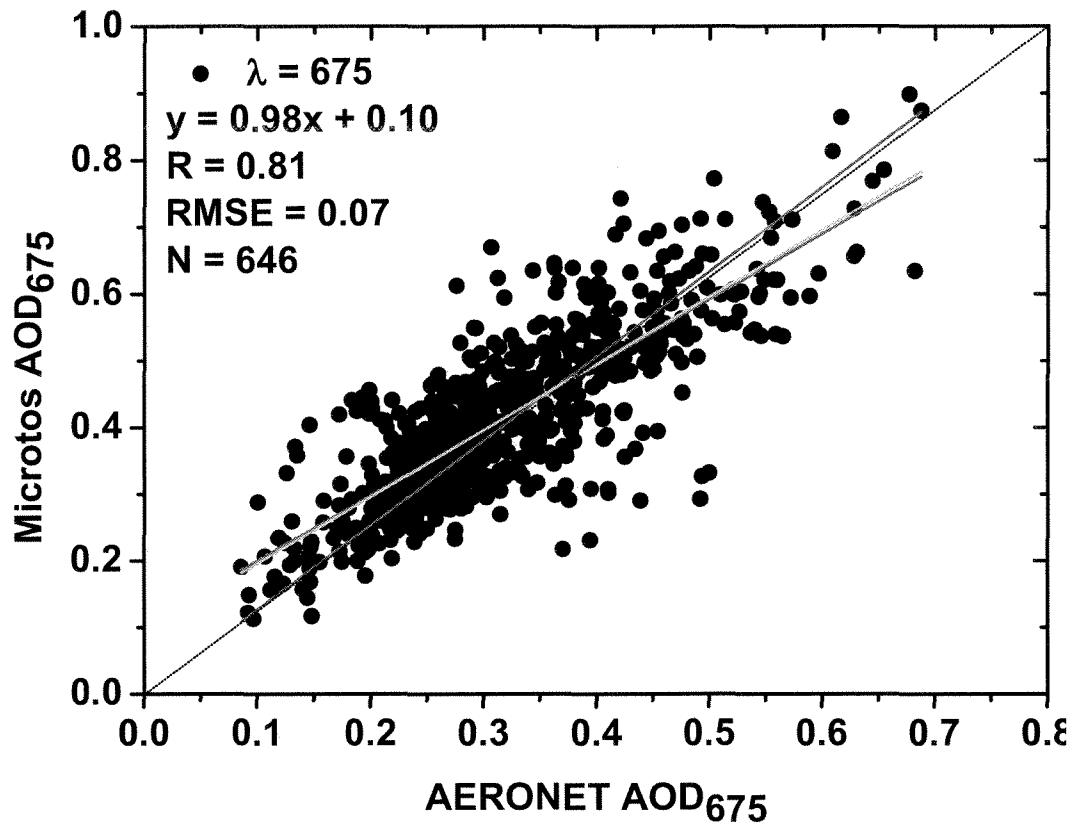


Figure10: Scatter plot of AERONET and Microtops AOD measurements at 675 nm during 2008-2010. (Red line is regression line and blue and green lines are forced lines at intercept = 0 and slope = 1 respectively; dotted black line is 1:1 line).

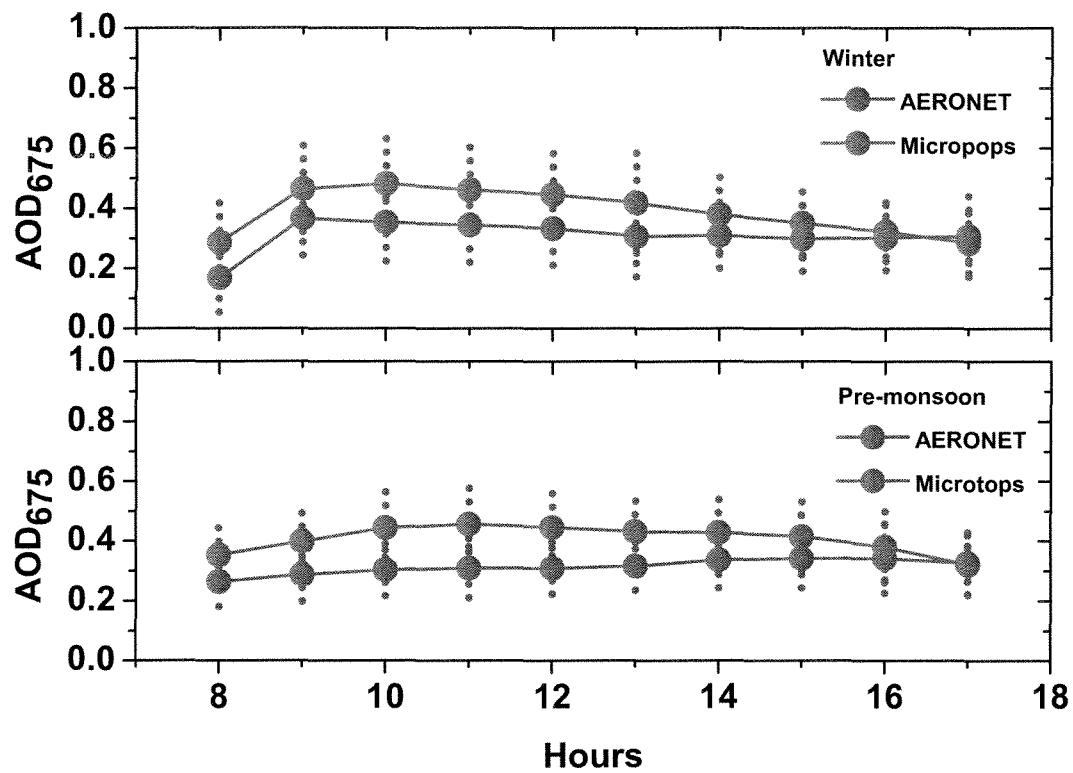


Figure 11: Seasonal inter-comparison of AERONET and Micropops II Sun-photometer during 2008-2010

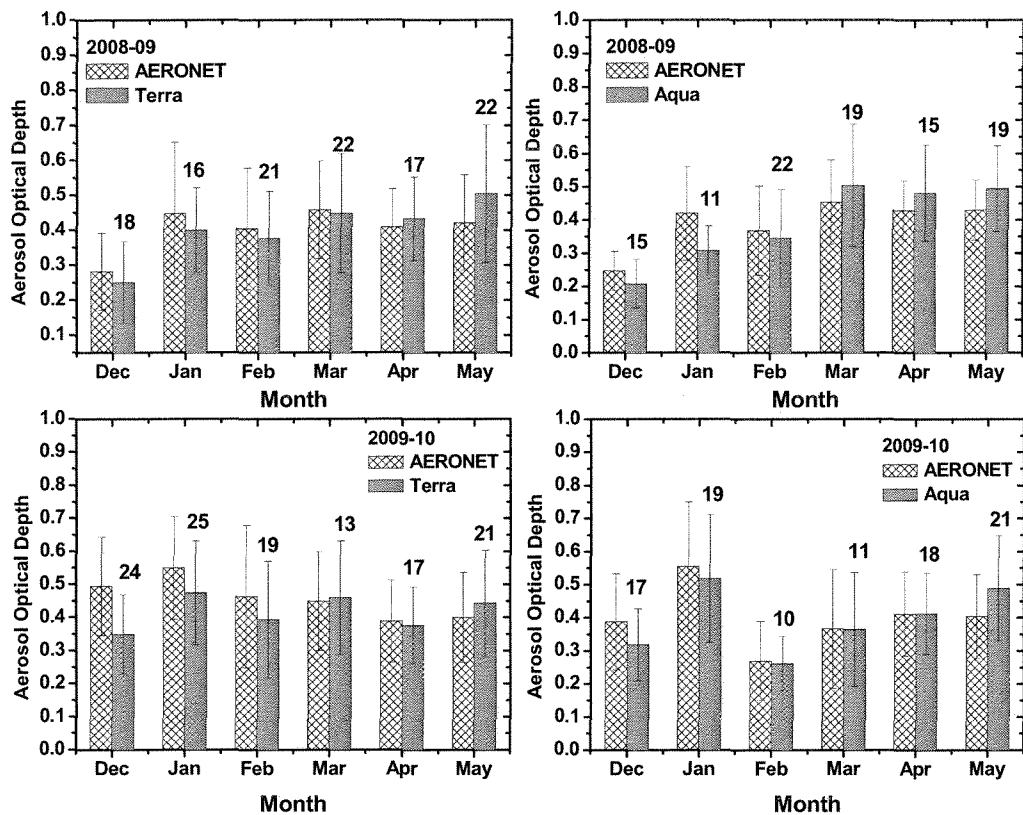


Figure 12: Monthly mean AODs for MODIS (Terra and Aqua) and AERONET during 2008-2009 and 2009-2010 over Pune.

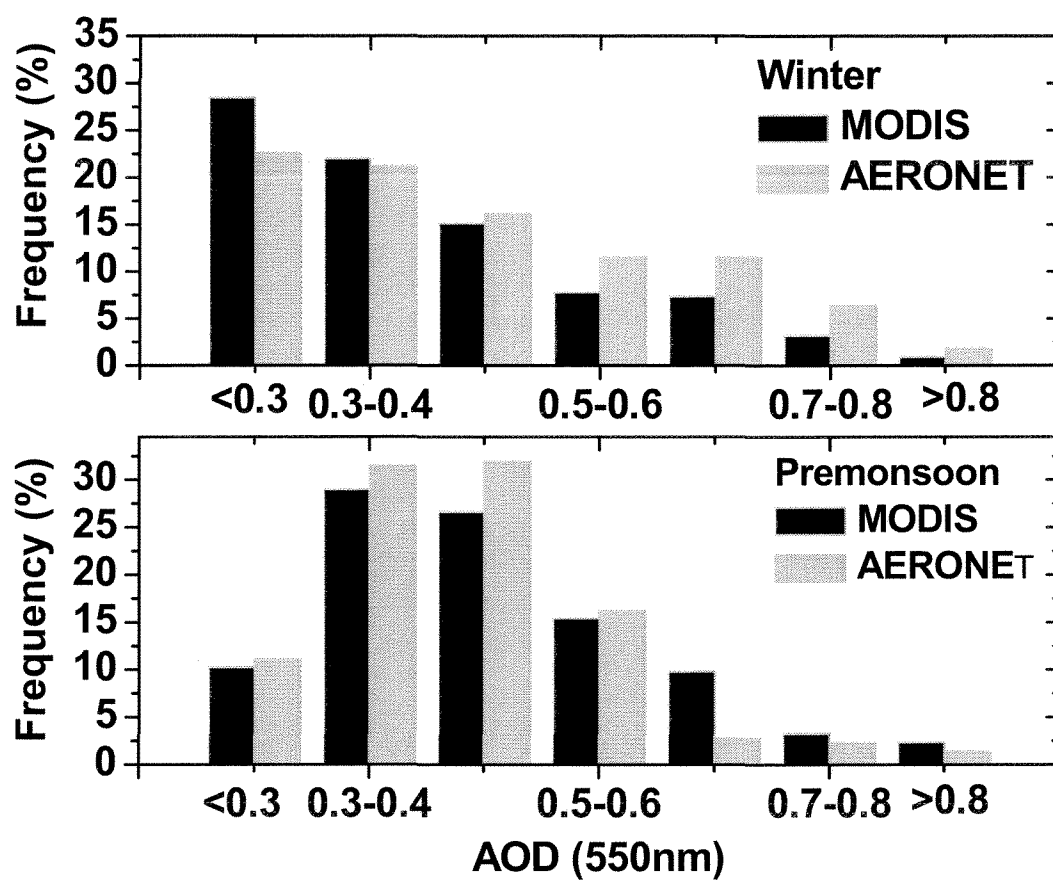


Figure 13: Seasonal frequency distribution of MODIS and AERONET AODs during Dec 2008-May 2010.